Science, Engineering and People with a Mission

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Pedersen, Jørgen Lindgaard

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Jørgen Lindgaard Pedersen
DTU Management Engineering
Technical University of Denmark
Mail: jlpe@man.dtu.dk

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Danish Wind Energy in Context 1891 – 2010

Jørgen Lindgaard Pedersen

Department of Management

Technical University of Denmark

Mail: jlpe@man.dtu.dk

ABSTRACT

Danish wind turbine development started in 1891 with establishment of a wind turbine for production of electricity for a folk high school and the local village community. The dominant figure was Poul La Cour, a physicist and meteorologist with a strong social and political consciousness. He made a well functioning architecture of the turbine, some important contributions to design of the blades and separation of water in oxygen and hydrogen as a method to have a stock of energy. The bottleneck for development was in science. A new theory of aerodynamics contributed to creating a new platform for development. During the period 1891 – 1918 the wind electricity was of importance especially in rural areas in Jutland where the wind is strong.

During the period 1918 -1976 alternate current was introduced in Danish electricity production and distribution also in rural areas and it resulted in a near death for wind energy. But still we have three important technical innovations – the Agricco turbine, the F.L.Smidth turbine and the Gedser turbine. Only during Second World War there was a strong demand for wind turbines.

Finally in the period 1976-2010 we have a continuous technological innovation period characterized first of all in growth in effect of turbines from 10-15 kW to 5-6 MW, clustering the turbines in wind parks onshore and today offshore. It is a very important techno-organizational innovation that with the Tvind turbine built as a 2 MW turbine 1975-78 a new concept called the component concept, where important modules could be bought from independent suppliers, was established. It was not only profit which drove the development. Resistance against a powerful industrial and political lobby was fuel for the first years after the First Energy Crisis 1973-74. The Tvind turbine is a strong case of that. Still that turbine was one of the decisive technical innovations.

1 INTRODUCTION

Just after the First Energy Crisis 1973-74 with quadrupling the oil prices many small producers in Denmark began manufacturing of wind turbines. They had not made wind turbines before. Now they bought or made themselves some modules as blades, gears and generators and assembled the modules on the top of a tower made of concrete or steel. During the 1970s they sold the turbines nearly only for the Danish market. In the period 1982-86 these companies produced and installed more than 7,000 turbines in California. After that market disappeared as a consequence of the stop of tax allowances at the end of 1986 most of these small companies went bankrupt. In fact only one of the companies survived. But new reconstructed companies came up with a stronger financial base and with a more broad international market orientation first of all towards Germany, U.K., Spain and other European countries. Later on most of the world has been a market for Danish wind turbines. The industry has now been one of the most important industries measured as export contributor at the same level as the pig industry and the pharmaceutical industry.

The development outlined above cannot be understood without some knowledge about the history of Danish wind turbine development and production starting up in 1891 and installed to a considerable extent in windy rural regions in Western part of Denmark until end of First World War. Some of the most important knowledge created during more than eighty years before the First Energy Crisis was known and documented and could be used in practice by some important persons when a need for that came up.

The aims in this paper are first of all to present the Danish wind energy history taking into account the broader history as far it is relevant as the context into which the wind energy development went on. A framework for presenting this history will be described. A second aim is an analysis of synergies and/or self destruction between science, engineering and political, organizational and commercial activities

2 A THEMATIC HISTORY OF DANISH WIND ENERGY 1891-2010

The first power station in Denmark was opened in Odense, one of the big provincial towns, in 1891. The second was established and opened in Copenhagen in 1892. It was less than a decade after Edison had started up the first power station in the world. The electricity produced was direct current (DC) which implied that only users located within three – four km from the power station could get access to electricity.

Wind energy as a source for production of electricity was already mentioned by Lord Kelvin in 1881[1]. A more direct inspiration came probably from the electrification in towns mentioned above. Already in 1887 we have the first wind turbine for production of electricity installed by the Scotch electrical engineer Professor James Blyth[2] In 1888 we have the American Charles F. Brush, educated as mining engineer, who during winter 1887/88 constructed a big wind turbine which charged batteries in the cellar of his home and laboratory. It worked well for more than twenty years[3]. The third pioneer was the Danish meteorologist and physicist Poul la Cour who from 1878 worked as a teacher in natural sciences and mathematics at the famous Danish folk high school Askov located in a small village with the same name in Western part of Denmark, in

[1] Salmonsens Konversationsleksikon, Anden udgave, Bind XXV, Copenhagen 1915-1930, in Danish, p. 224 citation from Poul la Cour, Forsøgsmøllen, Copenhagen 1900

[2] James Blyth (engineer), http://en.wikipedia.org/wiki/James_Blyth_(engineer)

[3] Danish Wind Industry Association, A Wind Energy Pioneer: Charles F. Brush, www.windpower.org

Jutland. From 1891 he got funds from government to establish and operate a test station for use of wind energy to produce electricity to rural districts in Denmark[4].

The history of Danish wind energy can and has been written in different ways. The above mentioned work by H. C. Hansen is a biographic way to describe the beginning looked through the life of the most important pioneer.The dissertation was defended and accepted at the Faculty of Science at Aarhus University. The author of the work was himself a teacher in the same subjects as Poul la Cour also at the Askov folk high school when he made his work nearly a century after. So he knew the wind science and technology topics very well.

In the following a framework has been used which allow to make an analysis of the economics of wind energy. Naturally because of this choice some information, maybe also important for an understanding of the development of wind energy, has been left out.

2. 1 A framework for describing the Danish wind energy history

Inspiration for the following framework comes from different authors. The productive forces – relations of production approach has naturally its background in Karl Marx's theory of historical materialism, the structure – agent model is often used in modern sociology e.g. in Anthony Giddens.

A pragmatic framework can be described in the following way:

- The technology with people, machines, equipment and raw material to catch energy from the wind
- Need and demand for electricity and need and demand for electricity generated by use of wind turbines
- Supply of electricity and supply of electricity generated by use of wind turbines
- Driving forces behind development of wind turbine design, effect and clustering
- The persons who made the work to maintain the technology, firms and organizations and create their renewal

2. 2 Birth and life of the Danish wind turbine and wind energy system 1891-1918

From Ørsted[5] in 1820 discovered the electromagnetism through Faraday's work in 1831 a machine to generate direct current was constructed by Pixii[6] in 1832. A generator is a machine which can transform kinetic energy into electricity. A motor can transform electricity into kinetic energy. In order to generate electricity another machine shall move a shaft with a speed of several hundred, 750-3600, revolutions per minute (rpm)[7]. This machine can be a steam machine or a turbine driven by steam or water. However because of differences in speed between the moving machine and the generator a gear system has to be inserted between the rotor hub and the generator[8].

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[4] The absolut best source about Poul la Cour is the doctoral thesis written by H. C. Hansen: Poul la Cour grundtvigianer, opfinder og folkeoplyser, 516 pages, in Danish, but including an English summary, pp. 489-500, Askov Højskoles Forlag, Askov 1985
[5] http://en.wikipedia.org/wiki/Electromagnetism
[6] http://en.wikipedia.org/wiki/Electrical_generator
[7] http://en.wikipedia.org/wiki/Wind_turbine_design
[8] Ibid

What Poul la Cour understood from the very beginning of his work with transforming of wind energy into electricity was the need to transform the slow speeds of wind turbine blades in the hub into much higher rmp. At the same time it was needed to transform the irregular speed of the wind into a regular speed of the rotor hub. The problems about transforming the slow wind speed into a much higher speed to be able to run the generator and at the same time make the speed regular was solved by developing a so called kratostat which was a primitive but efficient way to solve the problem[9]

But Poul la Cour also knew that the wind energy caught by the blades of the most efficient windmills of his days which was 7 percentages of total energy in the wind was so little that wind energy would be irrelevant in practical use for generation of electricity. Therefore he found very early in his work that he should have a much better theory of wind or what today will be called fluid mechanical theory of which aerodynamic theory about the wind close to solids is a part. In this way he could hope to get knowledge about how to catch more of the energy in the wind. Here he found that two Danish engineers H. C. Vogt and Johan Irminger already in beginning of 1890s had developed or maybe more correctly formulated rediscovered an alternative to Newtons aerodynamic theory where the lift from wind was seen as the source of energy in wind. Bernoulli and d'Alembert had already in 1738 and 1752 proposed such an alternative. The alternative was to accept that suction from wind on the backside of the blades were of higher importance. The importance of the work made by Vogt and Irminger was that they made tests in wind tunnels and showed the overwhelming importance of the suction forces[10,11].

What la Cour did was that he developed a model of an ideal turbine and calculated that it could catch 24 percentages of the energy in the wind under laboratory conditions. In mid-1980s the most effective turbine could catch 48 percentages. In a more correct comparison the la Cour turbine figure should have been 30 percentages[12]. In an empirical study it was found that the pre-la Cour turbine or rather mill caught 21 percentages of the ideal turbine. The la Cour turbine caught 80 percentages of the figure for the ideal turbine[13]. If we instead had made the comparison between two versions of turbines – the pre-la Cour and the la Cour version normalized to the whole area swept by the blades the figures would have been 6 respective 21 percentages which means that the la Cour turbine had an effiency four times the old turbine made without the new aerodynamic theory[14].

The second important aim for la Cour was to find a solution of the energy storing of the excess electricity produced in periods with good wind to be used in periods without sufficient wind. He made a solution in which water was decomposed in oxygen and hydrogen by use of electrolysis. By doing the chemical process $2H_2 + O_2 \rightarrow 2H_2O$. The left side is called "knaldgas" in Danish and the reaction can start with a small admission of energy. However what can happen is that there can be an explosion with much damage. So it is in practice not a very good way for storing excess electricity to use in periods without wind.

If we now look for the need and market for electricity in rural districts in Denmark in our period we can identify need from medium size and big farms in processing corn or milking. But more important was in fact

[9] H.C. Hansen, op.cit., pp. 182-186
[10] H.C. Hansen, op.cit., pp. 221-229
[11] Guy L. Larose and Niels Franck: Early wind engineering experiments in Denmark, in Journal of Wind Engineering and Industrial Aerodynamics 72 (1997), pp. 493-499
[12] H.C. Hansen, op.cit., p. 272
[13] H.C. Hansen, ibid, it shall be remembered that standardization to m^2 swept area has been made
[14] H.C. Hansen, op.cit., p.273

the demand for electricity for lighting[15]. In 1905 the total consumption of electricity in Denmark was 16, 7 million kWh. Half of that was used by tramways first of all in Copenhagen. Only 1.5 percentages of the electricity consumption came from rural districts[16]. 83 percentages of this rural consumption was for lighting. Part of the explanation of the little demand of electricity has to do with the high prices of electricity and low incomes for most people in rural districts. But still there was a movement in direction of electrification of rural districts and the villages. Wind electricity was here one of several proposals made in the debate sometime with use of accumulators and sometime in connection with generators driven by diesel or other fuels. Usually the organizational form for the rural production and distribution of electricity was cooperative. The isolated farms could not be a part of these wind electricity stations because of the very narrow limits for distribution of DC electricity. However a viable solution was developed called a wind electricity plant for farms. In 1907 11 percentages of farms with a size over 50 ha had such a wind turbine. In Northern part of Jutland the percentage was 20[17].

Already before First World War an important change began to take place in the national electricity system. More and more electricity became produced as alternate current (AC) which could be distributed over long distances without loss of energy. In this way an East and a West grid system was created in Denmark at that time. And the rural districts became up to the beginning of Second World War connected to these systems.

The wind electricity as part of the total consumption of electricity also in the rural districts began to stagnate and diminish the last few years before the start of First World War. After la Cour's death in 1908 up to First World War there were only three-four electricity stations using wind turbines. Denmark was neutral during the war but there were problems to get coal and oil. Even when it was possible to buy these fuels they were very expensive. Because of these problems a boom was created during the war. During winter 1917/18 about 105 small electricity stations used wind energy in connection with other energy sources. At the same time there were about 145 wind electricity plants in use at bigger farms and plants[18].

Which driving forces can be identified behind development of wind turbine design, effect and clustering in this period 1891-1918? On one side it is characteristic that after the la Cour had optimized the blades of his wind turbine, in Danish called "klapsejler", this four blade turbine was used without changes even during Second World War. A simple explanation of this low innovativeness can be found in the fact that production of DC electricity had as a consequence that each wind electricity station only produced to a very small market without networks between these" isolated islands". Therefore there were only small economics of scale in use of wind turbines. However there were some economics of scale in production of modules to the turbines even standardization could have been deeper and improved the economic gains. Some gains in positive externalities came from the fact that la Cour organized education of rural electricians and established the Danish Wind Electrical Society.

Finally we want to ask about the persons who made the new technology, firms and organizations and were responsible for its maintenance and renewal. From the establishment of the Danish State Test Station in Askov in 1891 until his death in 1908 Poul la Cour was in every respect a dominant figure or head not only of the official activities in wind energy – in some important scientific and inventive and engineering

[15] Steen B. Böcher: Danmarks Elektrificering, in Geografisk Tidsskrift, Bind 47 (1944), pp. 1-42, in Danish http://www.tidsskrift.dk/visning.jsp?markup=&print=no&id=69729
[16] Op.cit. p. 6
[17] H.C. Hansen, op. cit., p. 349
[18] H.C. Hansen, op.cit.,p.417

activities – but also in activities as education of electricians to install and maintain the electric parts of the wind electric system in 1904, and not to forget establishing the Danish Wind Electrical Society in 1903. In connection to this he had an extensive activity as a consultant to local people wanting to establish a wind electrical station.What has not been mentioned until now was that la Cour was also an important figure in the liberal political, social and cultural movement to establish a now order in Denmark against the reactionary forces in the Right political party with its supporters around the monarchy, military, diplomacy and church. The liberal forces had political parties, folk high schools, a Union of Danish Riflemen with close connections to the gymnastics and farmers associations. Especially the cooperative producers's associations owning dairies and slaughterhouses which were dominating these most important parts of Danish export oriented animal production from agriculture made this part of society to a stronghold for farmers. In fact la Cour was also active as chairman of the regional section in this Union of Danish Riflemen from 1881 until 1906[19]. For la Cour his wind energy activities were part of this much broader work in the liberal liberation movement with its social base in the farmers' position and life.

Naturally la Cour was not the only person of importance in this first phase of Danish wind energy development. It has already been mentioned above that the pioneers in establishing a modern aerodynamic science with a relevant theoretical foundation, the engineers Vogt and Irminger, had already made the fundamental work and tested the hypotheses in wind tunnels some years before la Cour made his work more focused on wind mills and turbines[20].

The millwrights, the persons who made the mills and turbines in this first period of wind energy have maybe a more important role in development of new wind energy technology than usually ascribed to. la Cour established contacts to several of these persons and their firms. One of the persons was millwright Chr. Sørensen with whom la Cour established contact in 1896. Sørensen had developed his own new design of wings or architecture of blades. He understood that he had to get his design tested and came into contact with H.C. Vogt mentioned above and la Cour. The important point was that Vogt and la Cour used wind tunnels to test the Sørensen design instead of full scale in natural wind. The tests showed that the Sørensen design with 16 blades was better than the so called wind rose with more blades. But la Cour also showed that four slim blades and installed with a more vertical angle would give a higher energy output than the Sørensen design. The only problem was that Sørensen had one important interest namely to get a patent and consequently money from his design. After many interactions between the two men including modifications of the Sørensen design la Cour could make tests telling about a high efficiency in the modified design[21]. The conflict between la Cour's near vertical installment of the blades, few blades and high rpm which came from his theoretical work combined with tests and the commercial interests from the business man who should sell his turbine developed from his experiences and his strong interest into taking out a patent was evident from beginning of the cooperation between the two persons representing science and engineering on one side and capital and engineering on the other side[22]

When la Cour in 1897 ordered a new wind turbine to the Test Station in Askov he asked Sørensen to deliver it as a six bladed version of the Sørensen turbine. However la Cour was not satisfied with this architecture because it not worked as expected. After two years he replaced it with a four bladed architecture in accordance with la Cour's ideal turbine model. From that time la Cour and Sørensen became enemies and

[19] H.C. Hansen, op.cit., pp. 142 ff.
[20] H.C. Hanen, op.cit., pp. 224-229
[21] H.C. Hansen, op.cit., pp. 230-234
[22] H.C. Hansen, ibid.

were in fight with each other through their respective barristers. The fight went on also in the national political system which paid for the Test Station in Askov. Even la Cour seems to have been the winner in this fight about the big blades architecture Sørensen still was very competitive in small turbines[23].

Only to complete the discussion about the relations between la Cour and the practicians – the millwrights with exception of Chr. Sørensen and the millers – it shall be stressed that there were close and good connections between all of them[24]. It is a common trait in these relations that these millwrights were not people with ambitions of inventions and innovations. Maybe from that fact there was no commercial motivated basis for conflict.

2. 2 Decline, stagnation and near death - and three innovations 1918-1976

When First World War ended November 1918 construction of new wind energy stations and wind electricity plants for farms stopped nearly immediately. Now it was possible in a realistic near future to be connected to the AC grid which could deliver electricity much cheaper and in a much more stable way than the wind energy could promise.

During the next 22 years there were not build and taken in use many new la Cour turbines in Denmark. But outside Europe some export seems to have taken place. The biggest producer of this klapsejler, Lykkegaard, eksported one turbine to Italian Somali in Africa and 26 to Venuzuela[25]. However during Second World War a strong renaissance for the la Cour klapsejler took place in Denmark. The biggest supplier of wind turbines in the interwar – period, the above mentioned Lykkegaards fabrikker, had a half man working with wind turbines in 1940 when Denmark was occupied by Germany and as a maximum of 40 man working with wind turbines during the war[26].

However there were three important technical renewals during the nearly sixty year period we are looking at here.

The first was the introduction of the so called Agricco turbine in 1918. It was developed by two Danish engineers Poul Vinding and Johannes Larsen. The turbine had blades inspired in their aerodynamics from propels used in airplanes, producing AC electricity using an asynchrony generator and delivering directly to the grid from a test station in Buddinge close to Copenhagen already in 1919 The effect of the turbines were different but often 40 kW. Interesting is that the efficiency was 50 percentages higher than the best la Cour klapsejlere. The price per kWh was DKK 0.30 in a test made in Oxford University 1924-25 if a battery was used and the half without battery. If items of older models were used the prices were DKK 0.80-0.90 or nearly three times so costly[27]. Even the innovative qualities in the Agricco turbine were not sufficient to let it survive, even there were some export and it was produced abroad. And in 1926 production stopped in Denmark.

During Second World War, from April 194o until May 1945, Denmark was occupied by Germany. The import of coal was half of normal quantity and import of oil was less than a fourth of normal size. With peat, brown coal and wood as the only domestic energy fuel interest for wind grew naturally very strong. In F. L.

[23] H.C. Hansen, op.cit., pp. 306-312
[24] H.C. Hansen: op.cit., pp.311-312
[25] H.C. Hansen, op.cit., p. 258
[26] H.C. Hansen, ibid
[27] Salmonsens Konversationsleksikon, note 1, ibid

Smidth & Co one of the biggest Danish industrial companies in cement and machines and even partner in production of airplanes it was after a short period with studies of the Agricco turbine and in cooperation with their partners in the airplane company, Kramme and Zeuthen owned and managed by the two mentioned engineers, decided to start up a production of wind turbines. They found that the turbines should have an effect of about 50 kW or more because smaller turbines would be a very competitive segment of the wind turbine market with many small engine works in which F. L. Smidth could not get a profit[28]. Inspiration for the FLS turbine came first of all from the Agricco turbine. But the FLS turbine should have a higher speed. During the occupation 12 two blades turbines and 7 three blades turbines were built[29]. The effect of the two blades version was estimated to be between 60 and 80 kW[30]. The three blades version produced AC electricity apparently with same effect as the DC turbines. In general the turbines worked well. However there were problems with resonance in the towers which were made of concrete. That had as a consequence that the towers had to be reinforced. Some minor problems with the blades had to be handled. But in general the turbines worked well and were running up to twenty years[31].

The third technical renewal was the so called Gedser Turbine which was developed and constructed in 1950s and taken into use in 1957. The man who formulated the vision behind the turbine was Johannes Juul. Born in 1887 he was a very young student at the first team of rural electricians in Askov 1903-04 with la Cour as one of his teachers. After a period working as independent electrician he had from 1926 a thirty years position in one of the big electricity distribution companies in which he made several inventions with his low volt cooker as an example. Even he did not had a formal education as an engineer but was to a high degree a self made man his work was research based and he was appointed to a member of one of the engineering societies in Denmark and could use the title engineer. He convinced his employer that it was relevant after the experiences during Second World War to make tests to find out if wind energy should be a part of Danish energy capacity. He built a turbine in 1950 with an effect of 10 kW and another in 1952 with an effect of 45 kW. Finally the Gedser turbine was ready for use in 1957. It had three blades, an asynchrony generator and a tip brake system on the blades. It was funded by Marshall financial resources and administrated by the national association of electricity generating stations but with Juul as its head. Its effect was 200 kW and it was the biggest turbine in the world of that time[32].

The most interesting trait with the Gedser turbine was that it can be considered on one side as the synthesis of the whole development from the first la Cour turbine in Askov in 1891 through its improvement during la Cour's life especially with realization of the new aerodynamics based on the work made by Vogt, Irminger and la Cour but also incorporating the new type of blades developed by Vinding and Jensen in the Agricco turbine and some experiences from the F L Smidth turbines from Second World War.

On the other side the Gedser turbine can be conceived as the prototype of the New Danish Wind Turbine which has been further developed and had much success from 1976 until today in 2010. It is not only the three blade architecture, automatic yaw system, asynchrony generator and a tip brake system. Also better economics than usually found at that time was important. The economics of wind electricity based on tests from the Gedser turbine was estimated by Government's Wind Power Committee in 1962 to costs of DKK

[28] Benny Christensen: FLS "Aeromotoren" – en dansk pionermølle, in Kapitler af vindkraftens historie i Danmark, 4. årgang, 2008, pp. 11-19, in Danish
[29] Ibid
[30] Ibid
[31] Ibid
[32] http://www.talentfactory.dk/en/pictures/juul.htm

17-19 per Gcal compared with DKK 8- 9 per Gcal for electricity produced by steam from coal or oil[33]. In the calculation it was not taken into account that there were no emissions of CO_2 from wind turbines.

2. 3 Rise of Danish and global wind energy 1976-2010

When the world learned the consequences from the quadrupling of oil prices from October 1973 until March 1974 there were many different reactions towards this so called First Energy Crisis. In Denmark there flourished what has been called a "popular spirit of engineering"[34]. That means there were lots of people with ideas about how to produce alternative energy, not only from wind but also from biogas and solar energy. In wind energy there were many persons or small groups with very different ideas about the future concept. For example many of these people thought that the Darrieus concept with its vertical shaft and whift should be the dominant design. Even in Vestas, the later world leader in production of wind turbines, the first work in the field was in that concept. Also at Risø Test Station there was a model of a Darrieus turbine. F. L. Smidth, the company from the turbines produced and installed during Second World War, had people supporting the concept[35]. Naturally the Second Energy Crisis 1978-80 with a new doubling of oil prices strengthened the the public opinion about the energy questions and made it evident that something had to be done.

What is important for understanding this "popular spirit of engineering" from 1973/74 until mid 1980s is a coincidence of different problems, conditions and struggles:

- Real problems with self-sufficiency of energy in a country without coal, oil and natural gas
- The relative production costs for energy from sustainable sources declined vis-à-vis fossil fuel
- A very long fight with people against industry and most of the political system in the question of nuclear power in Danish energy first of all with people concerned about waste deposits and industry concerned about cheap energy
- Knowledge in popular consciousness that we have had a long history with wind as energy source back from Danish history as a global navigation country and the la Cour tradition and experiences from two World Wars with massive energy problems

In the following table 1 we can look at some of the key figures in Denmark for the development of installed wind turbine generators measured in units and in capacity (effect) from end of 1970s until 1990. There are several interesting patterns which shall be stressed. Until 1984 included the capacity grows from 2.0 to nearly 8 MW per year in 1984. In the following years there is a strong growth until 80 MW per year in 1990.The average size of the new installed turbines grows from 13.3 kW in 1981 to 57.1 kW in 1984 and 243.9 kW in 1990. The cumulative capacity will naturally follow the development in yearly growth but on a higher level because of the long lifetime of turbines, usually twenty years. The capacity figures can be seen from 2.0 MW in 1979 to 26.7 MW in 1984 and 343.2 MW in 1990.

However these figures do not give an adequate description of level and development in production in Danish wind turbine industry in the period until 1990. First of all in the years 1982-1986 there was an enormous boom in export of turbines from Denmark to California. The background was a Californian tax allowance

[33] Fakta om vindenergi, M5 www.dkvind.dk/fakta/pdf/M5.pdf
[34] Preben Maegaard: Nogle af ideerne, der forsvandt undervejs, in Kapitler af vindkraftens historie i Danmark, 3. årgang, 2007, pp. 23-29, in Danish
[35] Ibid

scheme which made it very profitable for Californian citizens to invest in wind turbines. In this way the pollution intensity in California was expected to go down. In 1982 four of the biggest Danish wind turbine producers started to export to California and a little bit later three other companies accompanied the pioneers. As it can be seen from table 2 during the years 1982-1986 much more wind turbine capacity was built and installed in California by Danish wind turbine producers than installed in Denmark during the same timespan. 550 MW compared with 76 MW in Denmark.

Table 1.Installed wind energy in Denmark 1979-1990

Year	Number of units by year	Capacity MW by year	Average size of Wind Turbine Generator, MW	Cumulative Capacity, MW	Cumulative number of units
Until 1979	177	2.0	-	2.0	177
1980	200	2.5	-	4.5	377
1981	196	2.6	13.3	7.1	573
1982	163	5.6	34.4	12.1	736
1983	183	7.9	43.2	19.5	919
1984	126	7.2	57.1	26.7	1045
1985	326	23.1	70.9	49.8	1371
1986	358	31.7	88.5	81.5	1729
1987	311	33.0	106.1	114.5	2040
1988	457	82.0	179.4	196.5	2497
1989	469	65.7	140.1	262.2	2966
1990	332	81.0	243.9	343.2	3298

Source[36]: Table 2 in the reference p. 58

Table 2 Export of Wind Turbine Generators from Denmark to California 1982-1986

Year	Capacity ,MW	Number of units	Average size of Wind Turbine Generators, kW
1982	2.3	35	-
1983	20	300	65
1984	110	1568	70.2
1985	238	3486	68.4
1986	180	1888	95,3
Total	550	7277	

Source[37]: Table 3 in the reference p. 59

[36] Birger T. Madsen: Public Initiatives and Industrial Development after 1979, in WIND POWER – the Danish Way.From Poul la Cour to Modern Wind Turbines, The Poul la Cour Foundation, Askov 2009, pp. 52-59

The political system and its decision makers of politicians, civil servants and experts understood already in the end of 1970s the importance of establishing laws and regulations which could stimulate development of wind turbines and their realization in production and production and use of wind electricity. In a combination of voluntary contracts between electricity utilities and wind turbine owners and later on government regulation it became a precondition that the utilities should guarantee to buy a standard size of electricity during its expected lifetime, usually twenty years, and to a favorable price including a premium for environmental benefits and a premium for diminishing dependency of fossil fuel. Already in 1979 the majority in Parliament decided that owners of small wind turbines should have 30 percentages of their investment costs paid from government if the turbine was approved for quality in technical sense by an institution at Risø. That decision was important because it stimulated cooperation between turbine producers, wind turbine owners and Risø[38].

When the Californian tax allowances stopped at the end of year 1986 the Danish wind turbine industry exported 85 percentages of its production and most of it to California all companies with exception of one went bankrupt and/or had to make a recapitalization. During the following few years 1987-89 some dramatic changes took place inside the industry. First of all the new dominant companies oriented their development towards much bigger and more cost effective turbines and second activities were directed towards new markets in Germany and U.K. which both had public support to market schemes[39]. A consequence was that the wind turbine industry became dominated by Vestas as the biggest producer in Denmark and globally until today in 2010 with Siemens Wind Power the former Bonus with its head quarter located in Jutland as number two. LM Glasfiber which produces more than a third of the total global production of all blades for the turbines is still located in Jutland but owned by a British capital fund.

The development since 1990 can be characterized in the following way. First of all there has been a strong growth in installed capacity in Denmark until about 2002. After that time installed capacity has nearly disappeared until 2009 and 2010. Total cumulative capacity in 2008 is 3,150 MW and number of turbines 5,172[40]. That means an average size of the turbines to be 609.1 kW. The wind turbine capacity distributed according to size of the turbines can be seen in table 3[41]

Table 3. Wind turbine capacity in MW distributed on size of turbines 1980-2008

	-499 kW	500-999 kW	1000-1999 kW	2000- kW	Capacity total
1980	**3**				**3**
1990		**6**	**3**		**326**
1995		**103**	**5**		**600**
2000		**1518**	**279**	**56**	**2390**
2007		**1751**	**444**	**554**	**3124**
2008		**1757**	**443**	**621**	**3163**

Source: Reference 41, p. 9

In year 1990 turbines above 1000 kW was 1 per mille of total capacity; in year 2000 the share was 14 percentages and in 2008 the share had grown to 33.6 percentages.

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[37] Ibid, table 3 in the reference p. 59
[38] Ibid, p. 53
[39] Ibid, p. 59
[40] Birger T. Madsen: Facts About Wind Power in Denmark 2009, in WIND POWER – the Danish Way. From Poul la Cour to Modern Wind Turbines, The Poul la Cour Foundation, Askov 2009, p. 66
[41] Energistyrelsen: Energi i Danmark 2008, Energistyrelsen, Klima- og Energiministeriet, København 2009, p. 9, in Danish

3 ANALYSES OF DESIGN MODELS, SIZE DEVELOPMENT AND INNOVATION TYPES

In this section three problems will be analyzed from an economic perspective:

- Which factors can explain that after a short period starting mid-1970s with many different proposals realized at least as prototypes and often produced in few specimen times changed and the so called Danish Design Model for Wind Turbines became the only model not only in Denmark but globally?
- Which explanation can be given of the fact that the size of wind turbines has grown from about 10 – 15 kW mid-1970s to 5-6 MW today? And why seems off shore locations in wind parks to be the favorite location today?
- Which patterns can be identified in innovations in wind turbine development in respect to the so called science based innovations versus the so called experienced learning based innovations?

3. 1 Why many design models were defeated and the Danish model became dominant?

The very chaotic and flourishing period from mid 1970s until beginning of 1980s described above in the start of section 2. 3 ended suddenly more or less as it started up. Why? Immediately the answer can be given by saying that the big industrial companies accepted the Danish model with three blades, pitch regulation etc. But why were they accepting this model?

Different answers are possible:

First it shall be remembered that the third period in Danish wind energy started up with serial production of wind turbines which has been characteristically for the development after the so called Riisager turbines. From 1976 and the following years 76 turbines of these turbines in four series were produced and sold[42]. This development was of decisive importance for deepening the division of labour inside the companies and widening it between companies. The economic gains which can be profited from such a development in the division of labour depend on standardization in important modules, components and maybe architecture of the turbines. But in which direction this standardization will go can´t be said from this information alone.

Second a very important political decision shortly after the expansion in wind turbine building and development in many different directions just after the First Energy Crisis was a combination of three elements – 1) the electricity utilities were obliged to buy wind electricity produced in excess of owners consumption to own use and to a price above costs in conventional produced electricity, 2) a precondition for a turbine could be included in the above mentioned arrangement on guaranteed sale in quantity and price was that the turbine had been tested and fulfilled the hard claims on production of electricity during the expected lifetime of the turbine from the Wind Test Station located at Risø the center of the nuclear power interests in Denmark, and 3) it was clear that the subsidizing of wind turbines would be diminished over time in such a way that survival of the producers would depend very much on their ability to make the turbines still more productive from one turbine generation to the next.

Third when the Californian export market suddenly opened up during the years 1982 until end of 1986 with knowledge that it would disappear with the end of 1986 there was no time for experiments if a company wanted to earn the potential profits from that market. Therefore the well established Danish Wind Turbine Design became the design of the Gedser Turbine which as mentioned above was Johannes Juul's synthesis of

[42] Reference 33

the best characteristics from the development from la Cour's aerodynamics and the new more efficient propeller inspired blades in the Agricco turbine with size and AC production in the F.L.Smidth turbines. By choosing that model it was also possible for producers of modules especially blades to establish themselves and work on basis of a technological platform on which they could make differentiation according to individual wind turbine producers' wants. This development can be used in a model with resemblances from on one side evolutionary economics Giovanni Dosi[43] with concepts like cumulativeness and learning in the neighborhood and on another side evolutionare biology where Niles Eldredge and Stephen Jay Gould[44] has proposed the concept punctuated equilibrium. The idea is that relatively long time spans with gradually evolution of animals sometime will be interrupted by very fast and dramatic changes. The mechanism can be differentiation of one species in two or more species because of isolation of some part of the species so it would not be homogenized with the main population.

The explanation of the establishing of the Danish Wind Turbine Design is probably a combination of the three partial answers given above – introduction of serial or industrial production in the wind turbine industry, an interesting combination of economic and technical certainty for investors in wind turbines with a dynamics in the future subsidizes forcing the wind turbine producers to make continuously improvement in productivity, and finally the enormous pressure from the Californian market in the short period 1982-86 which made discussions about better design models academic when there was already a very good model, namely the design of the Gedser Turbine.

3. 2 Why continuous growth in wind turbine size, wind parks and off shore location after mid-1970s?

Since mid-1970 we can observe a continuously growth in the size of wind turbines measured by the effect of the individual turbine from 10-15 kW in the beginning until 5-6 MW today. An explanation often given is that costs of many of the modules and components in the modules do not grow proportional with growth in effect capacity. The generator will not need the double amount of material if its effect shall be the double. And usually the installment cost will not grow proportionally with the size of the different specimens. However these connections were also existent during the la Cour period 1891-1918 and here we can't identify such a tendency to continuous growth in turbine effect.

Several possible explanations can be given for the weakness in the economics of scale during the first period:

First an explanation can be that the markets during the first period were small isolated islands without network connections in flows of electricity because the electricity produced were DC which with the technology at that time could not be transported more than a short distance away from the electricity station. It was not because AC was not known or technical impossible to produce. Probably there were different arguments for the DC choice. One could be the fact that Edison had chosen DC in his first electricity station in the world 1882. Another could be economic that an AC grid between the small rural communities could not be viable. A third could be the benefit that DC electricity can be stored in batteries or accumulators which were important especially in the case of the big fluctuations in electricity produced from wind.

However there were some elements of economics of scale also in this first period. In production of turbines there were some factories which naturally had some modules which could be used in many turbines. And

[43] Giovanni Dosi: Technological paradigms and technological trajectories, in Research Policy, vol. 11, issue 3 (June 1982), pp. 147-162

[44] Punctuated equilibrium in http://en.wikipedia.org/wiki/Punctuated_equilibrium

some components could be used in different types of windmills/turbines. Especially many of the factories had started up with production of water pumps driven by small mills. Other had made mills for bigger farms for their grinding of grain as fodder for animals. There are in such a way elements of economics of scope in these factories. We know there was a division of labour between different companies with iron-foundries producing cogwheels. During the period 1900-1920 it is assessed that more than 20,000 wind mills and turbines were built in Denmark[45].

In use of wind turbines we can expect there were some economics of network because the Test Station in Askov published their results from its start in 1891. From 1904 there was an education of electricians specialized in wind electricity also in Askov. The year before the Danish Wind Electrical Society was founded with a journal and meetings. Finally we shall not forget la Cour's activities as a consultant and lecturer all over the country most of his time after 1891.

When the third period in Danish wind energy history started up immediately after the First Energy Crisis 1997-74 broke out it has been mentioned above that it was very important for some of the most important players e.g. Chr. Riisager that production should be serial so the benefits from industrial production and organization could be harvested. The Riisager turbines from 1976 were the first real mass produced turbines in Denmark. The serial production imperative became very fast accepted especially after the Californian export boom started up in 1982. It was evident that only producers with capacity for serial production could be able to deliver to this market. The seven Danish companies which produced and installed 7,277 turbines(and a good part of the 1,156 turbines installed in Denmark) on the other side of Earth during less than five years had until mid-1970 never worked with wind turbines but produced equipment as wagons or irrigation for agriculture or were startup companies and their activities in Denmark were not more than six years and usually less. On the other side the explosive growth from the Californian market was an incentive to find sub contractors for modules as blades or gears.

If we make a distinction between economics of scale in production of turbines, economics of scale in use of turbines and finally economics from logistics some interesting tendencies can be identified.

We have some figures in table 4[46] from which we can assess cost shares of the total turbine costs ex works which means which includes tower, blades and transport to the site but not foundation, grid connection and so on. The cost distribution is different in different types of turbines according to size, quality and efficiency. However our case which is a very big, 5 MW, turbine from the German REpower is still relevant to identify the economic most relevant components. There are three components or using a better term modules (tower, rotor parts and gearbox) which together costs 64 percentages of total cost of a wind turbine.

Table 5[47] shows figures from a medium sized turbine. Here we can observe that turbine costs ex works are about 75 percentages. Grid connection and foundation are substantial part of the other costs. It is also clear from the table that there are big variances in the individual cost elements. It has something to do with the fact that the data are collected from different European countries.

[45] Bruno Christensen: Lokal mølleproduktion i Vestjylland 1900-1920, in Kapitler af vindkraftens historie i Danmark, 1. årgang 2004,pp. 8-12, in Danish
[46] Søren Krohn, Poul-Erik Morthorst and Shimon Awerbuch: The Economics of Wind Energy. A report of the European Wind Energy Association, 2009,p.37
[47] Søren Krohn et al., op. cit., p.31

We want to get an estimate of investment costs and development of this figure over time. To do that we want to look at costs per swept rotor m^2 which is the area swept area. It can be argued that this area is a better measure or indicator of the production capacity of a turbine than the rated effect of the generator. From 1989 until 2004 the total cost per swept m^2 went down by 2 percentages per year. This development was broken in 2006 because of strong growth in demand for turbines, rising prices in steel and output constraints[48].

Economics of scale in use of turbines is not only to be explained from scale of the individual turbine. It is also important to understand that clustering the turbines in wind parks and locating these wind parks on

Table 4. Main components of a wind turbine and their share of the overall turbine cost for a 5 MW turbine

Component name	Percentages of overall turbine cost
Tower	26.3
Rotor blades	22.2
Rotor hub	1.37
Rotor bearings	1.22
Main shaft	1.91
Main frame	2.80
Gear box	12.91
Generator	3.44
Yaw system	1.25
Pitch system	2.66
Power converter	5.01
Transformer	3.59
Brake system	1.32
Nacelle housing	1.35
Cables	0.96
Other	11.36
Total	100

Table 5. Cost structure for a medium sized wind turbine in Europe

	Percentages of total cost	Typical percentages of other cost
Turbine (ex works)	68-84	-
Grid connection	2-10	35-45
Foundation	1-9	20-25
Electric installation	1-9	10-15
Land	1-5	5-10
Financial costs	1-5	5-10
Road construction	1-5	5-10
Consultancy	1-3	5-10

[48] Søren Krohn et al., op. Cit., pp. 42-44

locations with better wind will give improvement in use of the turbines. It is possible to reduce installment costs which shall be ascribed to scale effects in production including installment. Operation and maintenance which we can call economics of scale in use of the turbines will also be cheaper.

Specifically about logistic in location of wind parks we can observe a tendency during the last years to locate these parks off shore because the winds are stronger and more permanent than they will be on shore. The extra costs connected to off shore wind parks will be foundation and maintenance. Extra benefits can be harvested from much bigger turbines.

3. 3 Science, engineering and capacity for resource mobilization in wind turbine innovations

From the history of Danish wind energy we can identify different actors or groups of actors with access to different qualities and quantities of resources:

- Scientists
- Engineers
- Manufacturers
- People organized with a mission

Sometimes these different groups are working for the same purpose and differences are not destroying this work. In other situations there are internal contradictions which can make the work more difficult but also make a better result than would have been the case without these fights mentioned. Sometimes one or more groups have been the dominant actors. In other situations one or two of the groups or persons have been of critical importance. We shall only look at innovative including inventive activities

For example the innovation of the la Cour klapsejler would never have been a success case without the new aerodynamic theory developed by Vogt and Irminger and later on by la Cour himself. If we look at the period from the First Energy Crisis 1973-74 until establishing the modern wind turbine industry in the end of 1980s after the end of the Californian export boom the innovations in this fifteen years period were dominated by people which often were manufacturers but from outside the wind energy field. In fact we can also find examples of people as innovators where the driving force was a fight against nuclear power in Danish energy production.

In this section two cases will be considered:

1. The la Cour klapsejler
2. The Tvind turbine

3.3.1 The la Cour klapsejler

The klapsejler, the wind turbine developed by la Cour, was not an innovation made as a whole. It consisted of several modules and architecture. The most important inventions and innovations made by la Cour and the relations he established to make these technical renewals were:

- The kratostat and the first test turbine
- Storing of wind energy in hydrogen as medium
- Wind tunnel tests

- Development of new blades based on the new theory of aerodynamics

The main argument from la Cour for government money to establish the Wind Test Station in Askov in 1891 was la Cour's promise to find a way to store wind energy from windy periods to periods without much wind[49]. However it became soon evident that several other problems should be solved before he could find a solution of the energy storing problem he had promised government.

First of all he had the problem to transform the very irregular movement of wind into a regular movement which could be used to move a shaft connected with a generator producing electricity. He found a solution called a kratostat with cogwheels and belts which was effective and was used in many other connections than wind turbines. Here he seems to have worked only with his background as a physicist and his general ability as inventor which was considerable. Before his Askov time he had made lots of inventions especially in telegraphy where he developed a method to transfer several telegrams at the same time on the same line. He was known in media as Denmark's Edison[50].

After he had developed the kratostat la Cour had a method to produce electricity from wind. Now he could try to find a solution of the problem how to store excess electricity from windy periods and use it in times without wind enough. His method was to use electricity to hydrolysis of water and in this way get hydrogen and oxygen. This method he got from an Italian professor Garuti. By combining H_2 and O in this proportion he had what is in Danish called knaldgas which can be used as a gas to lighting. However the Garuti apparatus was not able to make a totally correct separation of water which resulted in explosions (the Danish word "knald" means "bang" in English!). He made some improvements of the equipment. However even the method could work it was still dangerous[51].

Now la Cour began to work with what maybe should be his most important contribution to wind turbine technology. It was very clear that the existing wind mills, the so called Dutch Mill was very ineffective for tapping energy from wind. It could only catch 7 percentages of the total energy. With so poor efficiency wind generated electricity could never be competitive to electricity produced by use of coal or oil to heat water to make steam and in this way run a generator. What he did was to make tests of different designs and proposals for other types of wind mills. Especially he established contact with millwright Sørensen. And in this way he learned how to make tests about effects from wind on blades. Not in real wind but with use of wind tunnel tests. He met H. C. Vogt the intellectual founder of the new aerodynamic theory and his partner Johan Irminger which had access to wind tunnels in the gas station where he was managing director. Without his learning about this new theory he could not have been able to understand how important the suction from the backside of the blade was for catching energy from the wind depending of the construction of the blade and the angle the blade had toward the vertical. So here we have a very important example on how a new basic scientific knowledge gave instruction to change the blades and their location on the mill and in this way improves the efficiency to catch energy from wind from 7 to about 25 percentages. It is important to acknowledge that Vogt and Irminger had made their scientific contribution without being governed of intention for helping construction of better wind turbines.

As mentioned above in section 2. 2 la Cour had two periods with contact with millwright Chr. Sørensen. In the first around 1896 he learned and became inspired a lot from Sørensen. In the second period they became

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[49] H.C. Hansen, op.cit., p.180
[50] H.C. Hansen, op.cit., p.189
[51] H.C. Hansen, op.cit., pp.191-209

enemies because they had very different opinions about the design of an ideal mill or turbine. la Cour wanted to make a design which followed his vision from his scientific based knowledge about aerodynamics. Sørensen had his practical experiences as a millwright with knowledge about how to make blades which at that time was from wood. Further Sørensen naturally had his business interests and la Cour his social and political interests. The conflict was also a conflict between two persons with strong wills.

In a concluding assessment of la Cour it is a remarkable fact that he incorporated most the functions mentioned above. He was a scientist, an engineer and a man who was able to inspire many other people as a teacher at the Folk High School Askov but also as a lecturer all over the country with people of very different background. He organized a Wind Electrical Society and an education of electricians specialized in wind electricity technology. The only activity where he was not able to get success seems to be as a manufacturer of his many inventions transformed into innovations.

3.3.2 The Tvind turbine

As mentioned above in section 2. 3 the First Energy Crisis October 1973-March 1974 had as immediately effect that many different people and from different motives started to think and take initiatives in order to find solutions of the Danish energy problems.

The Tvind School Community located in Western part of Jutland did the same. The motivation was to fight against the at that time strong pro-nuclear power political and business forces in Danish electricity production. They decided to build the biggest wind turbine in the world with an effect of 2 MW. At that time a typical wind turbine in Denmark had an effect of 10 – 15 kW. One thing is that it was seminal that hundreds of people without much concrete knowledge about wind turbines could engage themselves into such a project which all experts told was impossible to fulfill[52]. However in 1975 several hundreds of people began the work and in 1978 the turbine started up to deliver electricity to the grid and electricity and hot water to the School Community. Even today it works without problems.

In many respects the Tvind turbine represents innovations which twenty years later from mid-1990s have been standard in the big international wind turbine companies. It had revolving blades in contrast to fixed blades which was standard mid-1970s. It had a synchronous generator also in contrast to the usually asynchronous generator used in turbines at the time the project was planned. The blades were innovative in respect of aerodynamics and structural characteristics. Finally the turbine was innovative because it introduced the so called component wind turbine which in fact is a modular concept[53].

The Tvind turbine innovations are very interesting to follow because the Tvind people were not experts and acknowledged that. So they had to find relevant experts to help them with advices but still it was Tvind who made the decisions. Who were the experts? Naturally they were very different people depending of the specific problems.

If we look at development of blades a solution developed by professor Ulrich Hütter from Technical University in Stuttgart, Germany was selected. The solution was fibre glass ropes wrapped round nave bolts which made the blades stable fixed. The Tvind turbine builder got also help from people working at Risø in their work with development of blades. But the dominant Danish experts preferred other designs of blades

[52] Preben Maegaard: Tvindmøllen viste vej, in Kapitler af vindkraftens historie i Danmark, 5. årgang,2009, pp. 22-29, in Danish
[53] Ibid, pp. 23-24

for big turbines. But it was the Tvind concept which became the winning concept and used in industrial production[54].

The so called concept of the component wind turbine which was used in the Tvind turbine was maybe not totally new. We know that there are elements of that already back in the first period 1891-1918. But an important characteristic of the Tvind concept was that knowledge was open. For example knowledge about construction of blades was given for free. More than twenty independent companies could be established during the end of 1970s and start of 1980s first of all because they could buy blades and other main modules from specialized subcontractors. If you have the blades the companies could themselves manage the rest[55]. From the technical data of the Tvind turbine it can be seen that the generator was a second-hand ASEA generator from 1954. The gear box was a non-used ASEA reserve gear from a Swedish copper mine from 1958. The main shaft had been used in an oil tanker and was found with a ship breaker in Rotterdam. The tower and foundation, the blades and the nacelle were made by the Tvind people themselves with some advices from experts[56].

Compared with the first period in Danish wind turbine development where la Cour clearly was the head of nearly everything it is not so clear with the Tvind turbine. There are many different experts with their contributions. Still Amdi Petersen who was head of the Tvind School Community and also head of the organization responsible for building of the turbine seems to have had the overall coordination functions and at the same time insisted on specific technical solution e.g. the blade design[57]. However he was not a scientist nor an engineer so he could not make new contributions in these fields. But the component concept was probably a result of his way to think and organize.

4 CONCLUSIONS

From a perspective of Danish wind turbine history we can identify three distinct periods:

- 1891-1918
- 1918-1976
- 1976-2010

The first and the third of the periods are very innovative but in different ways. The first is very innovative in technical sense with several radical innovations during the first ten years. After that the period can be characterized with incremental technical improvements but important social innovations as education of electricians and establishing a wind electrical society. The third period has also ebb and flow in innovations, technical and social. However there can be identified a much more continuous development especially in technological development.

Explanations of the differences between the two periods can maybe be found in the fact that the first period was characterized by markets which were small islands protected from the outside world because of the DC system used. When it began to change into an AC system the wind turbine technology could not survive in

[54] Ibid, p.24
[55] Ibid
[56] Ibid, op.cit., p. 29
[57] Ibid, op.cit., p. 24

economic terms. The electricity was too expensive. The situation in the third period is different in several respects. Now environmental matters have been important and a premium has been paid from government because of CO_2 savings from use of wind energy technology. That is the sustainability argument. Another argument can be found in the fact that wind energy is a domestic resource compared with coal and oil. That is the self-sufficiency argument. But it was and still is very important that modern wind turbines are producing AC electricity for a world market.

The second period 1918-1976 is a special period. There are very weak demand for wind turbines in Denmark and also more generally. Still we have three important innovations – the Agricco turbine, the F.L.Smidth turbine and finally the Gedser turbine. With exception of the special situation during Second World War where everything could be sold these important innovations were not able to stimulate a market driven demand.

There is nothing general to be said about the relative strength in importance of science, engineering and political, organizational and commercial activities in development of wind energy. In the first period science was an important bottleneck. In the second period even important engineering progress could not neutralize the poor competitiveness in private economic sense. Finally in the third period a combination of industrialization of production and political mediated subsidizing of demand in a open world market have established a model with permanent growth in productivity because of growth in effect of turbines, wind parks and finally expansion of off shore location of these parks. The Tvind building of its 2 MW turbine established a new concept of building turbines, the so called component turbines.

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